The IRM
Quarterly
Summer 2007, Vol. 17 No. 2

Inside…

And Unknown Unknowns[1]…

on quantifying uncertainty in rock-magnetic properties

Mike Jackson
IRM

AMONG THE MOST ROUTINE PROBLEMS in mathematical physics is that of fitting a line to a set of experimental data. Routine, yes, but not as trivial as it may seem! There are many subtle and not-so-subtle considerations involved in evaluating whether a linear model is appropriate/adequate, in choosing an optimal fitting method, and in estimating the probability distribution of model parameters. Here we will illustrate some of these general considerations through the specific problem of high-field slope calculations based on magnetic hysteresis measurements.

Let's begin by assuming that a linear model is appropriate for a judiciously chosen subset[2] of the data in Fig 1. The generic equation for a line[3] ($y = mx+b$) can here be written as $M = \chi_{HF}H+M_S$, where M_S is the saturation magnetization and the linear high-field slope χ_{HF} represents the susceptibility of dia- para- and pure antiferromagnetic phases in the sample. The coefficients of the linear fit thus provide physically meaningful information about the magnetic mineralogy of a specimen; this is probably the simplest example of "unmixing" bulk magnetic data into discrete component contributions.

More generally it is a relatively straightforward example of a geophysical inverse problem (in which model parameters are determined from measured data sets). The problem is overdetermined, since the number of measurements far exceeds the number of parameters. Measurement errors are inevitable, so no line will fit the data perfectly, and we wish to find the one that fits "best", minimizing the sum of deviations in some appropriate sense[4].

Although the least-squares fitting method[5] is fast, elegant and powerful, let's begin instead with a lumbering brute-force approach. Like Gauss, we will evaluate the goodness-of-fit for a set of model parameters (χ_{HF}, M_S) by computing the sum of squared deviations $\chi^2 = \Sigma(M_i - (\chi_{HF}H_i+M_S))^2$ (where the statistical chi symbol should not be confused with that for susceptibility). We will simply trudge robotically through a grid of possible (χ_{HF}, M_S) models, calculating χ^2 as we go. The results (Fig 2) show the approximate coordinates of the best-fitting model, and just as importantly, they show (at least qualitatively) the uncertainty in the best-fit model parameters (i.e., the region of the model space where reasonable fits are obtained).

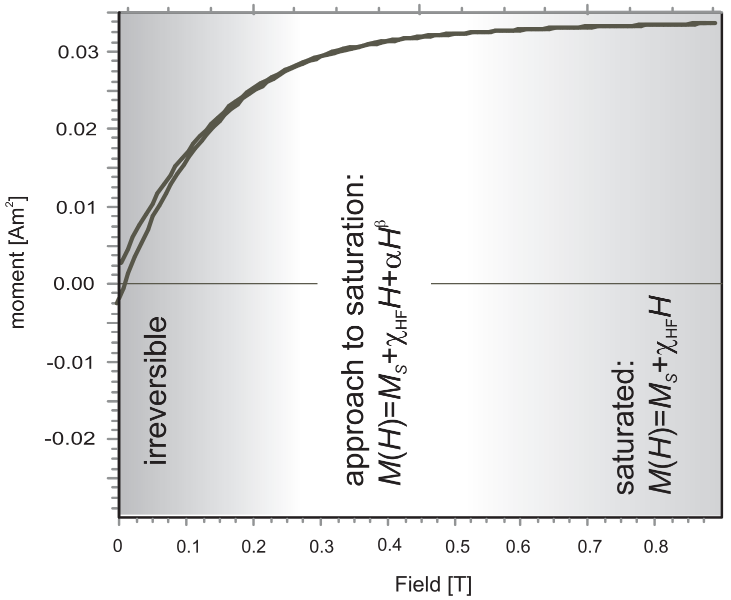


Fig 1. In sufficiently strong applied fields, ferromagnetic phases are saturated and their magnetization is constant (M_S); the linear high-field slope χ_{HF} is due to the field-independent susceptibility of the paramagnetic, diamagnetic and pure antiferromagnetic phases in the specimen. The approach to saturation is gradual, and the lower boundary of the saturated regime is not clearly defined.

If the standard assumptions of least-squares fitting (zero-mean, Gaussian-distributed measurement errors) are valid for this data set, the χ^2 contours map out statistical confidence regions for the "true" parameter values.

It is evident that the uncertainties in this case are negatively correlated, i.e., if our best-fit model $(\chi_{HF}, M_S)_{\text{best}}$ overestimates the true value of χ_{HF}, then it very probably *under*estimates M_S. It is also

cont'd. on p. 12…

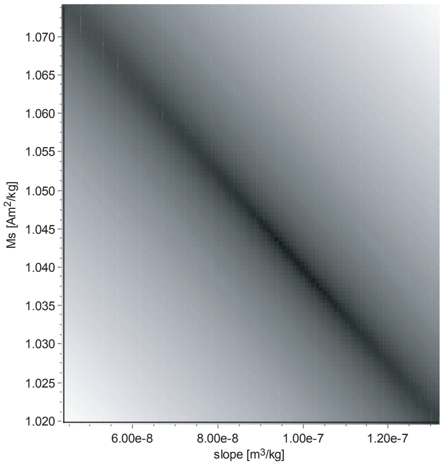


Fig 2. Misfit χ^2 for models (M_S, χ_{HF}) of the high-field data of Fig 1; darker shading indicates better fits.

Visiting Fellows' Reports

Rock Magnetic Investigation of mid-Pleistocene Lake Sediments from the Valles Caldera, NM

Linda Hurley
University of New Mexico
ldonohoo@unm.edu

THE GOAL OF THIS VISIT was to augment paleomagnetic and rock magnetic data acquired at the paleomagnetism laboratory at the University of New Mexico for the purpose of interpreting the environmental/sedimentological conditions of a long-lived (~200 ka) mid-Pleistocene lake that spans MIS 14 to MIS 10 (Fawcett et al., 2007) in the Valles Caldera, northern New Mexico. The Valles Caldera lake sediments were mostly eroded from adjacent rhyolite domes but these clay-rich sediments are also a mixture of fine detritus from dacites, basalt flows, ore deposits, and hydrothermally altered volcanic and sedimentary rocks. The sediment is well laminated throughout most of an ~ 80 m core (VC-3), but bioturbation and oxidation horizons a few cms thick are locally preserved. Desiccation cracks are also present in VC-3 and vary from a few tens of centimeters to about a meter in length. Electron microprobe data on magnetic separates support the presence of Fe-Ti oxides, sulphides, magnetite, and maghemite grains ranging from a few to tens of microns in size. I conducted measurements on bulk material from over two hundred sediment intervals and magnetic separates from VC-3 at the IRM in June, 2007. Several rock magnetic measurements were conducted on these sediments to quantify the contributions of these various magnetic phases, including high temperature susceptibility (Kappa Bridge), low temperature remanence (MPMS), frequency dependent susceptibility (Lakeshore), hysteresis measurements (VSM), and Mossbauer spectroscopy. Susceptibility response to elevated temperatures for both bulk samples and magnetic separates is characterized by a gradual decrease during heating, with occasional Hopkinson peaks at about 525º C, and a sharp drop in suceptibility by 575º to 580º C. The cooling curves often show higher susceptibility values than initial values due to alteration of unstable phases to magnetite. MPMS results show that the bulk sediment is dominated by paramagnetic and/or superparamagnetic material with little to no drop in remanence at any expected transition or isotropic points. Two exceptional samples show a sharp drop in remanence between 35 and 42 K, and differences over an order of magnitude between field cooled and zero field cooled remanence, similar to data obtained from siderite bearing sediments. Frequency dependant susceptibility determinations at low temperatures on a few specimens resulted in spectra typical of paramagnetic, superparamagnetic, and iron-titanium phases. Hystersis loops to 1 T acquired at room temperature are often slightly potbellied with a significant paramagnetic contribution. Most loops display an increase in moment beyond the initial saturation point such that the ascending part of the loop crosses over the initial saturation level and the loop never closes. Mossbauer spectroscopy data from magnetic separates are complex and support the presence of pyrrhotite, siderite, and a Fe^{3+} bearing magnetic phase with no measurable contribution from Fe^{2+}. Many unknowns remain in terms of characterizing the magnetic mineralogy of VC-3 sediments. For example samples with Curie temperatures documented at about 580º C, have a suppressed Verwey transition and no evidence of Fe^{2+} in the Mössbauer spectra data. More work is needed to characterize the ferrimagnetic components in terms of oxidation and cation substitution to successfully distinguish between intervals of the core where a detrital remanence is preserved (if at all) and intervals where authigenic minerals have replaced the detrital record. An updated interpretation of these data will be presented at the 2007 Fall AGU meeting. I wish to thank everyone at the IRM for their help with instrumentation use, suggestions, and insightful discussions about these complicated results.

Fawcett P.J., Heikoop J., Goff F., Anderson R.S., Donohoo-Hurley L., Geissman J.W., WoldeGabriel G., Allen C.D., Johnson, C.M., Smith S. J., and Fessenden-Rahn, J. (2007) Two Middle Pleistocene Glacial-Interglacial Cycles from the Valle Grande, Jemez Mountains, Northern New Mexico. Eds Kues B.S., Kelley S.A., and Leuth V.A., Geology of the Jemez Region II. New Mexico Geological Society, Soccoro, 58th Annual Fall Field Conference, p 409-417

Young Island Arc Tephras: Variations of Magnetic Properties with Depth and Implications for Devitrification

Jennifer L. Kelley
Southern Illinois University at Carbondale
jlkelley@siu.edu

DEVITRIFICATION IS A POST-SOLIDIFICATION PHENOMENON resulting in the nucleation of crystallites within glass or along its boundaries. As crystallites evolve over time and incorporate available elements including iron, the magnetic properties of the volcanic glass are likely to change as devitrification proceeds and new magnetic oxides form. Thirty-three samples have been collected through a 15.54 m-thick profile on the flank of Yasur volcano in the New Hebrides Island Arc. These samples represent continuous andesitic ash accumulation of a constant composition. Recent ^{14}C dating of the lowest sample revealed that the profile records 22,935±188 years of activity. The objectives of my M.Sc. research are to 1) address

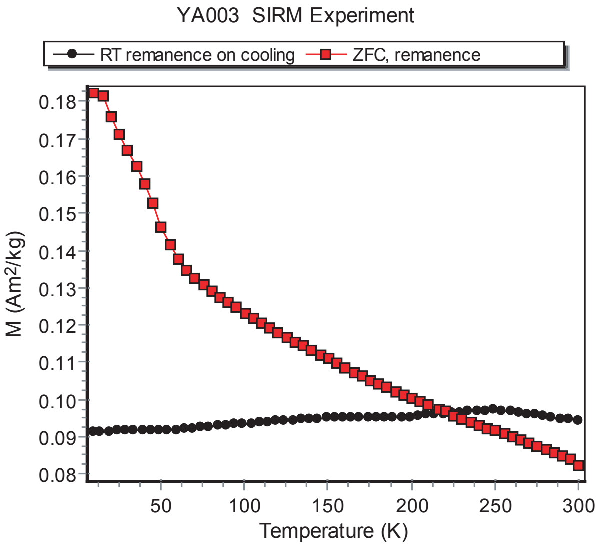


Figure 1: "ZFC, remanence" curve shows a more gradual loss of remanence above 50 K for sample YA003.

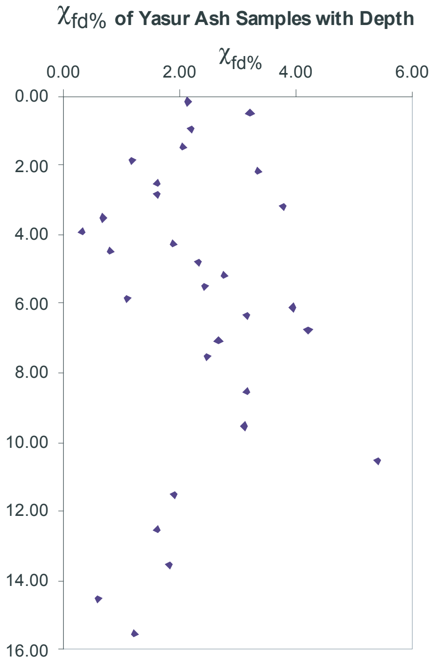


Figure 2: Frequency-dependence of magnetic susceptibility for all samples compared with depth.

the source of the magnetic properties of the material and any changes with depth/ age, and 2) determine at what point in the evolution of crystallites iron is incorporated from the surrounding amorphous matrix.

Preliminary magnetic measurements were performed at Southern Illinois University at Carbondale (SIUC) prior to my trip to the IRM. My goals for the IRM visit were to identify the magnetic phases present in the samples, and characterize any magnetic grain size variations with depth. Since frequency-dependence of susceptibility measurements are grain-size dependent, and increased devitrification leads to an increase in crystallite size, a magnetic granulometry analysis compared with degree of devitrification should highlight the relationship between these two parameters.

Several samples were evaluated using saturation isothermal remanent magnetization (SIRM) vs. temperature experiments performed on the MPMS to detect any ordering or phase transitions, unblocking temperatures, or temperature-dependent anisotropies. The zero-field cooled (ZFC) remanence curve on the resulting graphs showed a change to a more gradual loss of remanence with temperature at around 50 K; this was interpreted as a magnetic transition or crystallographic change that is intrinsic to titanomagnetites (TM).

Thermomagnetic experiments performed with the Kappabridge high-temperature susceptometer verified results obtained at SIUC and confirmed Curie temperatures (Tc). For the three samples measured, Tc= 347, 356, and 381°C, as determined by the first derivative of the thermomagnetic curve. Compositions of TM36, TM35, and TM31 respectively, were derived by the equation $Tc(°C) = 578 – 580\,x – 150\,x^2$, where x=ulvospinel content.

Frequency-dependence of susceptibility measurements were performed from 2- 300K using both the MPMS and the Lakeshore susceptometer to ensure all samples could be measured (the experiment takes from 8- 12 hours). The resulting graphs of temperature vs. susceptibility over a range of frequencies showed many similarities for all the samples: the in-phase portion of the graphs all had a slight hook at the lowest temperatures that indicated the paramagnetic contribution; a step-up feature in the susceptibility trend that further suggested a TM composition; and a frequency-dependence over a large range of temperatures that revealed the contribution of superparamagnetic grains to the magnetic properties. Frequency dependence for the samples was found to be from 0.33- 5.42% with an average of 2.30%. Variation with depth shows fluctuation over a small range, but not the anticipated curve that would indicate an increase in magnetic grain size with overall depth, at least for the bulk samples.

Work on the project continues and will include microscopy, Transmission Electron Microscopy (TEM), and X-ray fluorescence (XRF) to determine the extent of devitrification with depth/ age as recorded by the size and chemistry of crystallites within the glass. Repetition of the frequency-dependence of susceptibility experiment solely on the glass fraction of the ash may yield more valuable conclusions. If the evolution of crystallites can be measured and correlated with the magnetic properties of the glass, this methodology could be used to estimate the extent of devitrification.

I would like to thank the staff of the IRM, especially Mike, Pete, and Brian, for their insights, assistance, and warm hospitality during my visit.

Clark, D.A. 1997. Magnetic petrophysics and magnetic petrology: Aids to geological interpretation of magnetic surveys. Journal of Australian Geology and Geophysics 17 (2), 83 – 103.

Moskowitz, B., Jackson, M., and Kissel, C. 1998. Low-temperature magnetic behavior of titanomagnetites. Earth and Planetary Science Letters 157, 141-149.

Environmental Magnetism in Paleosols And Present Soils of Pampean Plain Argentina

Maria Julia Orgeira
University of Buenos Aires
orgeira@gl.fcen.uba.ar

Ramon Egli
Ludwig-Maximilians University, Munich
egli@geophysik.uni-muenchen.de

In recent years, Global warming has been strongly supported by direct observation of average atmospheric and oceanic temperature records, as well as widespread ice and snow melting and rising of mean sea level. The causes of this phenomenon are still debated, whereby a strong incidence is attributed to anthropogenic activities. However, the influence of natural phenomena such as variations of the solar constant, cannot be disregarded.

The geological perspective of this global phenomenon is of primary importance to evaluate future scenarios, since it is very well know that several global warming events have taken place naturally in the past. For example, early to middle Miocene was one of the warmest periods within Cenozoic times.

The last interglacial stage before present, the so-called Marine Isotopic Stage 5 (MIS 5), occurred around 120-110 ky before present and was characterized by maximum temperatures higher than present. A precise characterization of this warm isotopic stage, including its starting, evolution and ending, would provide relevant information on future climatic scenarios. On the other hand, medium-latitude paleoclimatic reconstructions on the Southern Hemisphere during warm periods are particularly important, since they can be linked to changes in atmospheric circulation patterns.

Studies on the MIS 5 record are actually scarce in South America, where useful sites are apparently limited to uplifted marine terraces, alluvial and colluvial deposits, and paleosols. In Argentina, Late Cenozoic continental deposits occur mainly within the Chacopampean Plain, which extends from 20°S to 40°S and the Andean piedmont (Fig 1). These deposits form a wide sedimentary cover of variable thickness. Pleistocene record is mainly composed of loessoid sediments, modified by pedogenic processes, which give rise to welded paleosols.

Several soil and loess-paleosols sequences from the Cordoba province (NW Argentina) have been studied (Sanabria and Arguello, 2003; Kemp et al, 2003 and Kemp et al, 2006), whereby the area is characterized by a mean annual temperature of 17° C and the mean annual precipitation is 840-960 mm/y .

MIS 5 has been identified at two sites in Pampean plain (Kemps et al, 2006), where it coincides with paleosols dated by luminiscense techniques. One of these sites is located in Lozada, Cordoba province (Fig 1), where a truncated paleosol developed on loess deposits and buried by fluvial sediments represents the continental record of the MIS 5 at this site (Kemp et al, 2006).

Magnetic iron oxides can provide critical information for paleoclimatic and paleoenvironmental reconstructions. The measurement of magnetic susceptibility has been applied successfully to the analysis of loess/paleosol sequences in China (literature). Although discrete correlations between modern rainfall and topsoil susceptibility has been obtained in Asia (Maher et al., 2003), opposed correlation or no correlation between magnetic bulk parameters and rainfall is typically observed in Argentina. The reason for this difference is unclear, and was a subject of investigation during the visiting fellowship of one of us (Orgeira) at the IRM during May 2006, while the other (Egli) was hardly trying to find a theory-of-all for the rock magnetic characterization of pedogenic minerals. We therefore combined our interests in trying to solve the "Argentinian paradox", considering two important aspects, namely 1) the significance of rainfall as a climatic proxy in soils, and 2) the significance of "susceptibility enhancement" as defined by Maher as a measure for the concentration of pedogenic iron minerals.

Orgeira et al. (2004), and Orgeira and Compagnucci (2006) proposed a model to explain the magnetic susceptibility of Argentinian soils which is based on a climatic proxy called potential water storage (PWS), which expresses essentially a balance between water input due to rainfall on one hand (precipitation, PP), and water loss due to evapotranspiration (ETP) on the other hand. The inorganic model is schematically illustrated on the next page.

A loess/paleosequence from Lozada (Cordoba province) has been characterized magnetically with room temperature susceptibility (Kappabridge), hysteresis measurements (VSM), low-temperature thermal demagnetization curves (MPMS) and frequency/temperature dependence of magnetic susceptibility (LakeShore). Detailed rock magnetic measurements have been performed on two samples of a recent soil profile collected in Corralito (Cordoba Province).

Profile measurements of the Lozada sequence are shown in Fig. 2-3, whereby the magnetic signature of

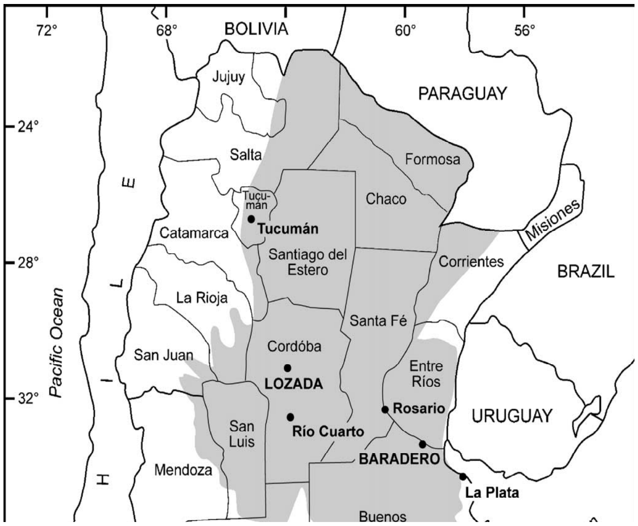
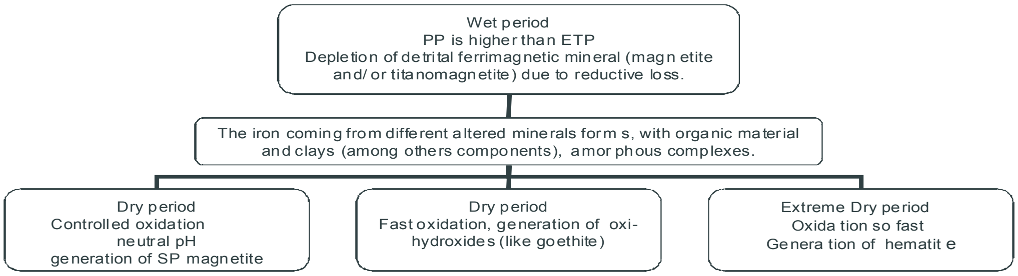


Fig 1. Distribution of loessic sediments in Argentina, South America. Lozada sampled site



Time increases from top to bottom

paleosoils is obviously different from the one found in China. In particular, the magnetic susceptibility of paleosols is not substantially different from that of loessic sediments. Coercivity parameters, on the other hand, are slightly but systematically different both in the modern soil and in the paleosol. These results are not conclusive in determining whether new iron mineral are forming in Lozada, or existing minerals are dissolved. To address this question, the magnetic results will be compared with sedimentological, geochemical, and micromorphological data.

Meanwhile, the presence of pedogenic iron oxides, in particular magnetite or maghemite, was investigated on two recent soil samples from Corralito and one recent soil sample from Lozada. One important difference with Chinese soils is represented by the high concentration of magnetic minerals of volcanic origin, which give raise to a very high "magnetic background". The unfavourable proportion between detrital and pedogenic minerals might alter significantly the interpretation of magnetic measurements, especially if detrital magnetic minerals are subjected to weathering. Magnetic unmixing techniques such as coercivity analysis (Egli, 2004) were not effective in separating the two magnetic components. Therefore, we tried to extract the detrital minerals using a powerful iron-boron magnet. Although the extraction was not completely effective, a clear difference can be seen between before and after magnetic extraction. Susceptibility measurements as a function of temperature and frequency allowed the identification of superparamagnetic (SP) minerals with a distribution of blocking temperatures similar – but not identical – to that of Chinese paleosols. It seems that the concentration of SP minerals changes little with depth, and remains high also in the loessic sediments. These results suggest a profound revision of our understanding of pedogenic processes.

These results, plus those of low temperature, are being analized with the geological information, such as sedimentological, geochemical and micromorphological data.

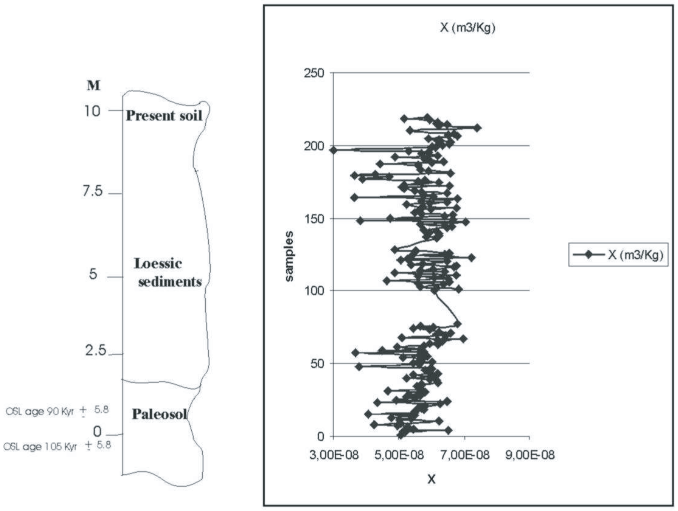


Fig 2. Schema of the studied sequence and magnetic susceptibility results

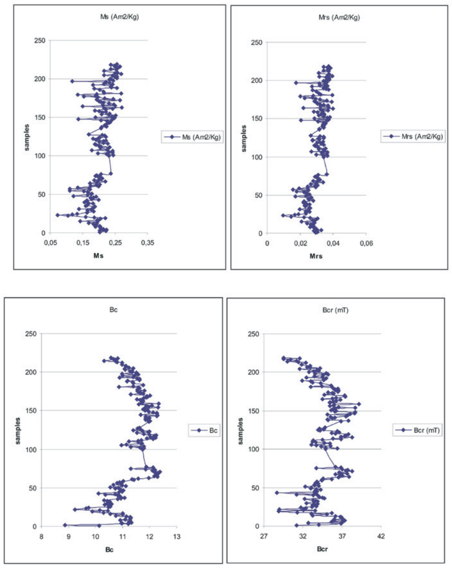


Fig 3 Magnetic parameters recorded in samples collected in Lozada loessic sequence. Córdoba Province, Argentina.

References

Egli, R; 2004.Characterization of individual rock magnetic components by analysis of remanence curves, 1. Unmixing natural sediments. Studia geophysica et geodaetica, 48, 391-446.

Kemp, R; Zarate, M.; Toms, P.; King, M.; Sanabria, J.and Argüello, G., 2003. Late quaternary paleosols, landscape evolution and climate change in the northern pampa, argentina. XVI INQUA Congress , Reno, Nevada. USA.

Kemp, R.A.; Zárate, M.; Toms P.; King M.; Sanabria, J. y Arguello, G., 2006. Late quaternary paleosols, stratigraphy and landscape evolution in Nothern Pampa, Argentina. Quaternary research. Vol 66 (1): 119-132.

Maher, B.A.; A. Alekseev and T. Alekseeva, 2003. Magnetic mineralogy of soils across the Russian Steppe: climatic dependence of pedogenic magnetite formation. Paleogeogr., Palaeoclimat, palaeoecol. 201:321-341.

Orgeira M.J.; Pereyra F.X. , Vásquez C., Castañeda, E. and Compagnucci, R., 2004. Environmental magnetism in present soils, Buenos Aires province , Argentina. Journal of South American Earth Sciences, in press.

Orgeira and Compagnucci (2006). Correlation between paleosol-soil magnetic signal and climate. Earth, Planets and Space (EPS), Special Issue " Paleomagnetism and Tectonics in Latinamerica"; 58 (10) : 1373-1380.

Sanabria, J. and Argüello, G., 2003. La evolución climática del holoceno, el desarrollo de los suelos y la edad de los sedimentos en la plataforma basculada, Córdoba, Argentina. Revista Cerrados. Dpto. de Geociencias. Universidad .Estadual de Monte Claro. Brasil. vol 1 – nº 1: pp 107- 117.

Visiting Fellows Program

Next proposal deadline April 30, 2008
see www.irm.umn.edu for details; or email irm@umn.edu.

FELLOWS FROM THE SECOND HALF OF 2007.

Nathan Church; *University of Cambridge*; High precision magnetic characterization of single-crystal and polycrystalline magnetite - ulvospinel (Fe_3O_4 - Fe_2TiO_4) solid solution

Linda Hurley; *University of New Mexico*; Rock Magnetic Investigation of mid-Pleistocene lake sediments from the Valles Caldera, NM

Paul Kelso; *Lake Superior State University*; Rock magnetic characterization of deformation localization recognized from magnetic fabrics (AMS and AARM) in the lower crust, Arunta Block, central Australia

Tomas Kohout; *Univ. of Helsinki*; and **Andrey Kosterov**; *Kochi University*; Low-temperature magnetic properties of the Neuschwanstein EL6 meteorite and characteristic magnetic mineral phases

Suzanne McEnroe and **Karl Fabian**; *Geological Survey of Norway*; Exchange coupling in natural nanoscale materials

Junsheng Nie; *University of Rhode Island*; Study on magnetic enhancement mechanisms of the Red-Clay sediments on the Chinese Loess Plateau

Belén Oliva-Urcia; *Universität Karlsruhe (TH)*; Crustal magnetization and magnetic petrology from hot-spot related basalts

Michael Petronis; *New Mexico Highlands University*; and **Brian O'Driscoll**; *Trinity College, Dublin*; Magnetic Mineralogy of the Western Granite, Isle of Rum, Scotland

---

2008 International Conference on Rock Magnetism and its Earth Science Applications

June 2-7, 2008
Institut d'Études Scientifiques de Cargèse, Cargèse, Corsica (France)

SAVE THE DATE! With anticipated joint sponsorhip by the National Science Foundation (US), the Centre National de la Recherche Scientifique (France), and the Istituto Nazionale di Geofisica e Vulcanologia (Italy), the primary focus will be in-depth discussion of fundamental aspects of rock and mineral magnetism, and applications in global geophysics, tectonics, and surficial environmental studies. An explicit aim is to explore new mineralogical and microanalytical techniques, and nanoscale magnetic structures and phenomena.

As if all this were not enough, the occasion will also mark the official retirement of Subir Banerjee, the founder and leading light of the Institute for Rock Magnetism and the Santa Fe Conference series, and will celebrate his career and his vital contributions to our field.

Organizing Committee

Bruce Moskowitz, Institute for Rock Magnetism (IRM) University of Minnesota

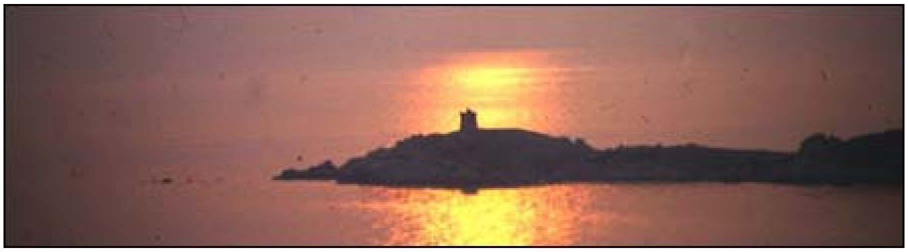
Pierre Rochette, Le Centre Européen de Recherche et d'Enseignement des Géosciences de l'Environnement (CEREGE), Aix-en-Provence, France

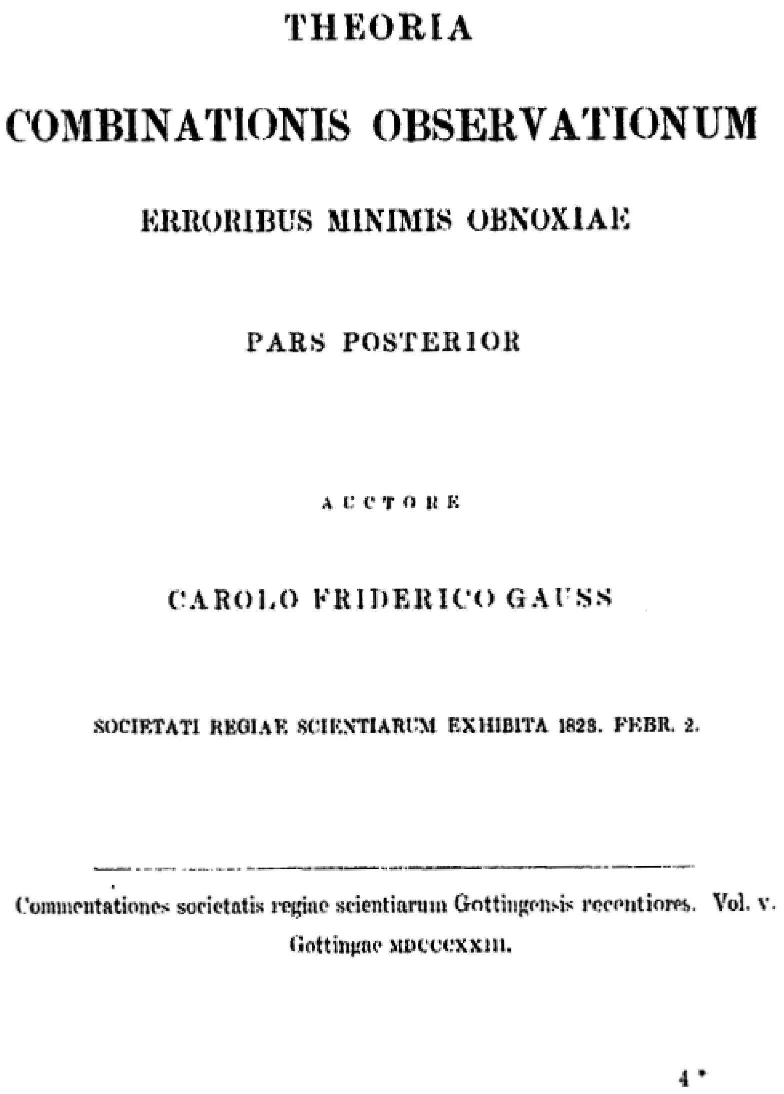
Andrew Roberts, University of Southampton, Southampton, UK

Fabio Florindo, Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy

Joshua Feinberg, Institute for Rock Magnetism (IRM) University of Minnesota

Mike Jackson, Institute for Rock Magnetism (IRM) University of Minnesota





THEORIA

COMBINATIONIS OBSERVATIONUM

ERRORIBUS MINIMIS OBNOXIAE

PARS POSTERIOR

AUCTORE

CAROLO FRIDERICO GAUSS

SOCIETATI REGIAE SCIENTIARUM EXHIBITA 1823. FEBR. 2.

Commentationes societatis regiae scientiarum Gottingensis recentiores. Vol. v.
Gottingae MDCCCXXIII.

4*

Current Articles

A list of current research articles dealing with various topics in the physics and chemistry of magnetism is a regular feature of the IRM Quarterly. Articles published in familiar geology and geophysics journals are included; special emphasis is given to current articles from physics, chemistry, and materials-science journals. Most abstracts are taken from INSPEC (© Institution of Electrical Engineers), Geophysical Abstracts in Press (© American Geophysical Union), and The Earth and Planetary Express (© Elsevier Science Publishers, B.V.), after which they are subjected to Procrustean culling for this newsletter. An extensive reference list of articles (primarily about rock magnetism, the physics and chemistry of magnetism, and some paleomagnetism) is continually updated at the IRM. This list, with more than 10,000 references, is available free of charge. Your contributions both to the list and to the Abstracts section of the IRM Quarterly are always welcome.

Alteration & Remagnetization

Ricordel, C., et al., 2007, Triassic magnetic overprints related to albitization in granites from the Morvan massif (France): Palaeogeography Palaeoclimatology Palaeoecology, v.251, no.2, p.268-282.

Anisotropy

Esmaeily, D., et al., 2007, Magnetic fabrics and microstructures of the Jurassic Shah-Kuh granite pluton (Lut Block, Eastern Iran) and geodynamic inference: Tectonophysics, v.439, no.1-4, p.149-170.

Hrouda, F., 2007, Anisotropy of magnetic susceptibility of rocks in the Rayleigh Law region: Modeling errors arising from linear fit to non-linear data: Studia Geophysica et Geodaetica, v.51, no.3, p.423-438.

Maes, S. M., et al., 2007, The Sonju Lake layered intrusion, northeast Minnesota: Internal structure and emplacement history inferred from magnetic fabrics: Precambrian Research, v.157, no.1-4, p.269-288.

Palmer, H. C., et al., 2007, Magnetic fabric studies of the Nipissing sill province and Senneterre dykes, Canadian Shield, and implications for emplacement: Canadian Journal of Earth Sciences, v.44, no.4, p.507-528.

Pares, J. M., et al., 2007, Paleocurrent directions from paleomagnetic reorientation of magnetic fabrics in deep-sea sediments at the Antarctic Peninsula Pacific margin (ODP Sites 1095, 1101): Marine Geology, v.242, no.4, p.261-269.

Sant'Ovaia, H., et al., 2007, Emplacement of the Monchique alkaline massif (SW Portugal): Microstructures and magnetic fabric constraints: Geochimica et Cosmochimica Acta, v.71, no.15, p.A876-A876.

Anomaly Sources and Magnetic Petrology

Kato, H., et al., 2007, Characteristics of crustal magnetic structures in the Tsushima (Ulleung) and Japan Basins from vector magnetic anomalies: Earth Planets and Space, v.59, no.7, p.887-895.

Saito, T., et al., 2007, Magnetic petrology of the 1991-1995 dacite lava of Unzen volcano, Japan: Degree of oxidation and implications for the growth of lava domes: Journal of Volcanology and Geothermal Research, v.164, no.4, p.268-283.

Ueda, Y., 2007, Magnetizations of the seamounts in the Izu-Ogasawara arc with special reference to the origin of their normal polarity biases: Earth Planets and Space, v.59, no.7, p.897-909.

Biogeomagnetism

Bazylinski, D. A., et al., 2007, Modes of biomineralization of magnetite by microbes: Geomicrobiology Journal, v.24, no.6, p.465-475.

Behrends, T. and Van Cappellen, P., 2007, Transformation of hematite into magnetite during dissimilatory iron reduction - Conditions and mechanisms: Geomicrobiology Journal, v.24, no.5, p.403-416.

Chen, A. P., et al., 2007, First-order reversal curve (FORC) diagrams of natural and cultured biogenic magnetic particles: Journal of Geophysical Research-Solid Earth, v.112, no.B8,

Komelli, A., 2007, Molecular mechanisms of magnetosome formation: Annual Review of Biochemistry, v.76, p.351-366.

Solov'yov, I. A. and Greiner, W., 2007, Theoretical analysis of an iron mineral-based magnetoreceptor model in birds: Biophysical Journal, v.93, no.5, p.1493-1509.

Wiltschko, W., et al., 2007, The magnetic compass of domestic chickens, Gallus gallus: Journal of Experimental Biology, v.210, no.13, p.2300-2310.

Chemistry and Physics of Magnetic Minerals

Barbier, A., et al., 2007, Surface termination of hematite at environmental oxygen pressures: Experimental surface phase diagram: Physical Review B, v.75, no.23,

Chan, M. A., et al., 2007, Models of iron oxide concretion formation: field, numerical, and laboratory comparisons: Geofluids, v.7, no.3, p.356-368.

Chirita, P., et al., 2007, Pyrrhotite oxidation in weakly acidic solutions: Geochimica Et Cosmochimica Acta, v.71, no.15, p.A171-A171.

Guyot, F., et al., 2007, Dissolution of magnetite in hydrothermal solutions: Kinetics and speciation by in situ X-ray absorption spectroscopy: Geochimica Et Cosmochimica Acta, v.71, no.15, p.A365-A365.

Henderson, S. P., et al., 2007, Schwertmannite transformation to hematite by heating: Implications for pedogenesis, water quality and CO2/SO2 export in acid sulfate soil landscapes: Geochimica Et Cosmochimica Acta, v.71, no.15, p.A394-A394.

Izaola, Z., et al., 2007, Revision of pyrrhotite structures within a common superspace model: Acta Crystallographica Section B-Structural Science, v.63, p.693-702.

Janovec, V. and Litvin, D. B., 2007, Scanning of magnetic space groups and the analysis of non-magnetic domain walls: Acta Crystallographica Section A, v.63, p.407-411.

Komorida, Y., et al., 2007, Pressure effects on gamma-Fe2O3 nanoparticles: Journal of Magnetism and Magnetic Materials, v.310, no.2, p.E800-E802.

Morcos, R. M., et al., 2007, The energetics of hematite dissolution in iron-oxide-rich melts: In situ high-temperature calorimetric studies: American Mineralogist, v.92, no.7, p.1064-1070.

Roh, Y., et al., 2007, Microbial leaching of iron from magnetite under aerobic and anaerobic environments: Geochimica Et Cosmochimica Acta, v.71, no.15, p.A847-A847.

Wehber, M., et al., 2007, In-situ X-ray synchrotron high-pressure measurements of magnetite: Geochimica et Cosmochimica Acta, v.71, no.15, p.A1097-A1097.

Wenzel, M. J. and Steinle-Neumann, G., 2007, Nonequivalence of the octahedral sites of cubic Fe3O4 magnetite: Physical Review B, v.75, no.21,

Whitehouse, M. J. and Fedo, C. M., 2007, Microscale heterogeneity of Fe isotopes in > 3.71 Ga banded iron formation from the Isua Greenstone Belt, Southwest Greenland: Geology, v.35, no.8, p.719-722.

Data Processing and Analysis

Heslop, D. and Dillon, M., 2007, Unmixing magnetic remanence curves without a priori knowledge: Geophysical Journal International, v.170, no.2, p.556-566.

Environmental Magnetism and Paleoclimate Proxies

Han, J. T., et al., 2007, Spatial and temporal patterns of grain size and chemical weathering of the Chinese Red Clay Formation and implications for East Asian monsoon evolution: Geochimica Et Cosmochimica Acta, v.71, no.16, p.3990-4004.

Hanesch, M., et al., 2007, Lithological and pedological influences on the magnetic susceptibility of soil: Their consideration in magnetic pollution mapping: Science of the Total Environment, v.382, no.2-3, p.351-363.

Hayashida, A., et al., 2007, Environmental magnetic record and paleosecular variation data for the last 40 kyrs from the Lake Biwa sediments, Central Japan: Earth Planets and Space, v.59, no.7, p.807-814.

Liu, Q. S., et al., 2007, What do the HIRM and S-ratio really measure in environmental magnetism?: Geochemistry Geophysics Geosystems, v.8,

McIntosh, G., et al., 2007, The magnetic properties of particles deposited on Platanus x hispanica leaves in Madrid, Spain, and their temporal and spatial variations: Science of the Total Environment, v.382, no.1, p.135-146.

Sroubek, P., et al., 2007, Historical climatic record from flood sediments deposited in the interior of Spiralka Cave, Czech republic: Palaeogeography Palaeoclimatology Palaeoecology, v.251, no.3-4, p.547-562.

Torrent, J., et al., 2007, Magnetic enhancement and iron oxides in the upper Luochuan loess-paleosol sequence, Chinese Loess plateau: Soil Science Society of America Journal, v.71, no.5, p.1570-1578.

Venuti, A., et al., 2007, Magnetic proxy for the deep (Pacific) western boundary current variability across the mid-Pleistocene climate transition: Earth and Planetary Science Letters, v.259, no.1-2, p.107-118.

Yang, T., et al., 2007, Magnetic signature of heavy metals pollution of sediments: case study from the East Lake in Wuhan, China: Environmental Geology, v.52, no.8, p.1639-1650.

Zhang, W. G., et al., 2007, Magnetic properties and geochemistry of the Xiashu Loess in the present subtropical area of China, and their implications for pedogenic intensity: Earth and Planetary Science Letters, v.260, no.1-2, p.86-97.

Extraterrestrial Magnetism

Bell, M. S., 2007, Experimental shock decomposition of siderite and the origin of magnetite in Martian Meteorite ALH84001: Geochimica Et Cosmochimica Acta, v.71, no.15, p.A75-A75.

Ebel, D. S., 2007, Paleomagnetic evidence for localized chondrule formation and rapid parent body accretion in the protoplanetary disk: Meteoritics & Planetary Science, v.42, p.A38-A38.

Kletetschka, G., et al., 2007, Utah and Czech Mars analog concretions; Aquatic hematite and goethite characterization: Geochimica et Cosmochimica Acta, v.71, no.15, p.A493-A493.

Klingelhofer, G., et al., 2007, Jarosite and goethite identified by Mossbauer spectroscopy on the surface of Mars: Mineralogical evidence for aqueous processes: Geochimica et Cosmochimica Acta, v.71, no.15, p.A494-A494.

Kohout, T., et al., 2007, Daubreelite and troilite as a source of cometary and minor body magnetism in cold environment: Meteoritics & Planetary Science, v.42, p.A85-A85.

Nozawa, J., et al., 2007, 3-D colloidal crystals of magnetite in the Tagish Lake carbonaceous chondrite: Geochimica Et Cosmochimica Acta, v.71, no.15, p.A726-A726.

Ogawa, Y. and Manga, M., 2007, Thermal demagnetization of Martian upper crust by magma intrusion: Geophysical Research Letters, v.34, no.16,

Rochette, P., et al., 2007, Sampling asteroid surfaces using magnets: Meteoritics & Planetary Science, v.42, p.A131-A131.

Rochette, P., et al., 2007, Magnetic classification of achondrites: Meteoritics & Planetary Science, v.42, p.A132-A132.

Rochette, P., et al., 2007, Trends in the meteorite flux since 1800: Historic versus astronomic modulations: Meteoritics & Planetary Science, v.42, p.A132-A132.

Nishioka, I., et al., 2007, Paleomagnetism of basalts from lonar impact crater: Meteoritics & Planetary Science, v.42, p.A119-A119.

Thomas-Keprta, K. L., et al., 2007, Re-evaluation of the “Life on Mars” hypothesis: Origin of carbonate-magnetite assemblages in Martian meteorite ALH 84001: Meteoritics & Planetary Science, v.42, p.A148-A148.

Instruments and Measurement Techniques

Tsuchimoto, M., et al., 2007, Evaluation of magnetic field hysteresis and flux creep of a QMG coil magnet: IEEE Transactions on Applied Superconductivity, v.17, no.2, p.2390-2393.

Wack, M. and Matzka, J., 2007, A new type of a three-component spinner magnetometer to measure the remanence of rocks at elevated temperature: Earth Planets and Space, v.59, no.7, p.853-862.

Weiss, B. P., et al., 2007, Paleomagnetic analysis using SQUID microscopy: Journal of Geophysical Research-Solid Earth, v.112, no.B9,

Magnetic Field Records and Geomagnetism

Brendel, K., et al., 2007, An analysis of the fluctuations of the geomagnetic dipole: Physics of the Earth and Planetary Interiors, v.162, no.3-4, p.249-255.

Chambodut, A., et al., 2007, Geomagnetic jerks from the Earth’s surface to the top of the core: Earth Planets and Space, v.59, no.7, p.675-684.

Courtillot, V. and Le Mouel, J. L., 2007, The study of earth’s magnetism (1269-1950): A foundation by peregrinus and subsequent development of geomagnetism and paleomagnetism: Reviews of Geophysics, v.45, no.3,

Courtillot, V. and Olson, P., 2007, Mantle plumes link magnetic superchrons to phanerozoic mass depletion events: Earth and Planetary Science Letters, v.260, no.3-4, p.495-504.

De Santis, A., 2007, How persistent is the present trend of the geomagnetic field to decay and, possibly, to reverse?: Physics of the Earth and Planetary Interiors, v.162, no.3-4, p.217-226.

Goguitchaichvili, A., et al., 2007, Paleomagnetism of the Eastern Alkaline Province (Mexico): contribution to the time-averaged field global database and geomagnetic instability time scale: Earth Planets and Space, v.59, no.7, p.775-783.

Gratton, M. N., et al., 2007, Absolute palaeointensity variation during a precursor to the Matuyama-Brunhes transition recorded in Chilean lavas: Physics of the Earth and Planetary Interiors, v.162, no.1-2, p.61-72.

Gubbins, D., 2007, Geomagnetic constraints on stratification at the top of Earth’s core: Earth Planets and Space, v.59, no.7, p.661-664.

Gubbins, D., et al., 2007, Correlation of Earth’s magnetic field with lower mantle thermal and seismic structure: Physics of the Earth and Planetary Interiors, v.162, no.3-4, p.256-260.

Hatakeyama, T., 2007, Effects of the site distribution and the prior information on the inverted geomagnetic field model: a case study applying the ABIC method to the synthetic datasets: Earth Planets and Space, v.59, no.7, p.703-709.

Herries, A. I. R., et al., 2007, Archaeo-directional and -intensity data from burnt structures at the Thracian site of Halka Bunar (Bulgaria): The effect of magnetic mineralogy, temperature and atmosphere of heating in antiquity: Physics of the Earth and Planetary Interiors, v.162, no.3-4, p.199-216.

Hofmann, D. I. and Fabian, K., 2007, Rock magnetic properties

and relative paleointensity stack for the last 300 ka based on a stratigraphic network from the subtropical and subantarctic South Atlantic: Earth and Planetary Science Letters, v.260, no.1-2, p.297-312.

Korte, M. and Thebault, E., 2007, Geomagnetic repeat station crustal biases and vectorial anomaly maps for Germany: Geophysical Journal International, v.170, no.1, p.81-92.

Mochizuki, N., et al., 2007, Further K-Ar dating and paleomagnetic study of the Auckland geomagnetic excursions: Earth Planets and Space, v.59, no.7, p.755-761.

Plenier, G., et al., 2007, Origin and age of the directions recorded during the Laschamp event in the Chaine des Puys (France): Earth and Planetary Science Letters, v.259, no.3-4, p.414-431.

Roberts, A. P., et al., 2007, High-resolution evidence for dynamic transitional geomagnetic field behaviour from a miocene reversal, McMurdo Sound, Ross Sea, Antarctica: Earth Planets and Space, v.59, no.7, p.815-824.

Sakuraba, A. and Hamano, Y., 2007, Turbulent structure in Earth's fluid core inferred from time series of geomagnetic dipole moment: Geophysical Research Letters, v.34, no.15,

Shibuya, H., et al., 2007, Paleomagnetism of Unzen volcano: A volcanic record (Senbongi excursion) of the Iceland Basin event and the Brunhes VGP distribution for Japan: Earth Planets and Space, v.59, no.7, p.763-774.

Takahashi, F., et al., 2007, A numerical study on magnetic polarity transition in an MHD dynamo model: Earth Planets and Space, v.59, no.7, p.665-673.

Tanaka, H., et al., 2007, Perspectives of geomagnetism: Geodynamo, paleomagnetism, and rock magnetism - Tribute to Prof. Masaru Kono - Preface: Earth Planets and Space, v.59, no.7, p.649-650.

Tanaka, H., et al., 2007, Paleointensities from Tertiary basalts, Inner Mongolia and Hebei Province, northeastern China: Earth Planets and Space, v.59, no.7, p.747-754.

Tarduno, J. A., Cottrell, R. D., Watkeys, M. K. and Bauch, D., 2007, Geomagnetic field strength 3.2 billion years ago recorded by single silicate crystals: Nature, v.446, no.5, p.657-660.

Verbanac, G., et al., 2007, On long-term trends in European geomagnetic observatory biases: Earth Planets and Space, v.59, no.7, p.685-695.

Yamamoto, Y., et al., 2007, Paleomagnetism of the Datong monogenetic volcanoes in China: paleodirection and paleointensity during the middle to early Brunhes Chron: Earth Planets and Space, v.59, no.7, p.727-746.

Yamazaki, T. and Kanamatsu, T., 2007, A relative paleointensity record of the geomagnetic field since 1.6 Ma from the North Pacific: Earth Planets and Space, v.59, no.7, p.785-794.

Yang, T. S., et al., 2007, Early and middle Matuyama geomagnetic excursions recorded in the Chinese loess-paleosol sediments: Earth Planets and Space, v.59, no.7, p.825-840.

Yokoyama, Y., et al., 2007, Geomagnetic 100-ky variation extracted from paleointensity records of the equatorial and North Pacific sediments: Earth Planets and Space, v.59, no.7, p.795-805.

Magnetic Microscopy and Spectroscopy

Beleggia, M., et al., 2007, Quantitative domain wall width measurement with coherent electrons: Journal of Magnetism and Magnetic Materials, v.310, no.2, p.2696-2698.

Belin, T., et al., 2007, In situ and time resolved study of the gamma/alpha-Fe2O3 transition in nanometric particles: Journal of Solid State Chemistry, v.180, no.8, p.2377-2385.

Fischer, H., et al., 2007, Magnetite in bacteria: A FMR study: Geochimica Et Cosmochimica Acta, v.71, no.15, p.A281-A281.

Fischer, P., et al., 2007, Magnetic soft X-ray microscopy: Imaging spin dynamics at the nanoscale: Journal of Magnetism and Magnetic Materials, v.310, no.2, p.2689-2692.

Franke, C., et al., 2007, Identification of magnetic Fe-Ti oxides in marine sediments by electron backscatter diffraction in scanning electron microscopy: Geophysical Journal International, v.170, no.2, p.545-555.

Goering, E. J., et al., 2007, Absorption spectroscopy and XMCD at the Verwey transition of Fe3O4: Journal of Magnetism and Magnetic Materials, v.310, no.2, p.E249-E251.

Krasyuk, A., et al., 2007, Magnetic stray fields of patterned permalloy structures investigated by photoemission electron microscopy: Applied Physics a-Materials Science & Processing, v.88, no.4, p.793-796.

Mahadevan, S., et al., 2007, X-ray diffraction-based characterization of magnetite nanoparticles in presence of goethite and correlation with magnetic properties: Physica E-Low-Dimensional Systems & Nanostructures, v.39, no.1, p.20-25.

Magnetic Transitions

Janu, Z., et al., 2007, Glass-like and Verwey transitions in magnetite in detail: Journal of Magnetism and Magnetic Materials, v.310, no.2, p.E203-E205.

Larese-Casanova, P. and Scherer, M. M., 2007, Morin transition suppression in polycrystalline (57)Hematite (alpha-Fe2O3) exposed to Fe-56(II): Hyperfine Interactions, v.174, no.1-3, p.111-119.

Li, Y. W., et al., 2007, Spin moment over 10-300 K and delocalization of magnetic electrons above the Verwey transition in magnetite: Journal of Physics and Chemistry of Solids, v.68, no.8, p.1556-1560.

Krol, G., et al., 2007, Studies of magnetic axis switching phenomenon in magnetite: Journal of Alloys and Compounds, v.442, no.1-2, p.83-85.

Neal, J. R., et al., 2007, Magneto-optical study of the Verwey transition in magnetite: Journal of Magnetism and Magnetic Materials, v.310, no.2, p.E246-E248.

Prozorov, R., et al., 2007, Magnetic irreversibility and the Verwey transition in nanocrystalline bacterial magnetite: Physical Review B, v.76, no.5,

Smirnov, A. V., 2007, Effect of the magnetic field applied during cooling on magnetic hysteresis in the low-temperature phase of magnetite: First-order reversal curve (FORC) analysis: Geochemistry Geophysics Geosystems, v.8,

Tabis, W., et al., 2007, Magnetic and structural studies of magnetite at the Verwey transition: Journal of Alloys and Compounds, v.442, no.1-2, p.203-205.

Zukrowski, J., et al., 2007, AC magnetic susceptibility under pressure and Mossbauer effect studies of the isotropy point T-IP in magnetite: Journal of Alloys and Compounds, v.442, no.1-2, p.219-221.

Magnetization & Demagnetization Processes

Biggin, A. J. and Perrin, M., 2007, The behaviour and detection of partial thermoremanent magnetisation (PTRM) tails in Thellier palaeointensity experiments: Earth Planets and Space, v.59, no.7, p.717-725.

Brinkman, A., et al., 2007, Magnetic effects at the interface between non-magnetic oxides: Nature Materials, v.6, no.7, p.493-496.

Chuev, M. A., 2007, Generalized Stoner-Wohlfarth model and the non-Langevin magnetism of single-domain particles: JETP Letters, v.85, no.12, p.611-616.

Fiorillo, F., et al., 2007, Measuring the hysteresis loop of permanent magnets with the pulsed field magnetometer: IEEE Transactions on Magnetics, v.43, no.7, p.3159-3164.

Garming, J. F. L., et al., 2007, Low-temperature partial magnetic self-reversal in marine sediments by magnetostatic interaction of titanomagnetite and titanohematite intergrowths: Geophysical Journal International, v.170, no.3, p.1067-1075.

Gattacceca, J., et al., 2007, The effects of explosive-driven shocks on the natural remanent magnetization and the magnetic properties of rocks: Physics of the Earth and Planetary Interiors, v.162, no.1-2, p.85-98.

Yu, Y. J., et al., 2007, A linear field dependence of thermoremanence in low magnetic fields: Physics of the Earth and Planetary Interiors, v.162, no.3-4, p.244-248.

Magnetostratigraphy and Geochronology

Blackburn, T. J., et al., 2007, Magnetite (U-Th)/He dating and its application to the geochronology of intermediate to mafic volcanic rocks: Earth and Planetary Science Letters, v.259, no.3-4, p.360-371.

Clyde, W. C., et al., 2007, Basin-wide magneto stratigraphic framework for the bighorn basin, Wyoming: Geological Society of America Bulletin, v.119, no.7-8, p.848-859.

Colman, S. M., et al., 2007, Age model for a continuous, ca 250-ka Quaternary lacustrine record from Bear Lake, Utah-Idaho (vol 25, pg 2271, 2006): Quaternary Science Reviews, v.26, no.7-8, p.1192-1192.

Deng, C. L., et al., 2007, Magnetochronology of the Feiliang Paleolithic site in the Nihewan Basin and implications for early human adaptability to high northern latitudes in East Asia: Geophysical Research Letters, v.34, no.14,

Elmore, R. D. and Dulin, S., 2007, New paleomagnetic age constraints on the Decaturville impact structure and Weaubleau structure along the 38th parallel in Missouri (North America): Geophysical Research Letters, v.34, no.13, Hao, Q. Z. and Guo, Z. T., 2007, Magnetostratigraphy of an early-middle Miocene loess-soil sequence in the western Loess Plateau of China: Geophysical Research Letters, v.34, no.18,

Housa, V., et al., 2007, Boreal-tethyan correlation of the Jurassic-Cretaceous boundary interval by magneto - and biostratigraphy: Stratigraphy and Geological Correlation, v.15, no.3, p.297-309.

Osete, M. L., et al., 2007, Magnetostratigraphy of Early-Middle Toarcian expanded sections from the Iberian Range (central Spain): Earth and Planetary Science Letters, v.259, no.3-4, p.319-332.

Tanguy, J. C., et al., 2007, Mount Etna eruptions of the last 2,750 years: revised chronology and location through archeomagnetic and Ra-226-Th-230 dating: Bulletin of Volcanology, v.70, no.1, p.55-83.

Torfstein, A., et al., 2007, U-Th, delta O-18 and paleomagnetic dating of a mid-Pleistocene lacustrine sequence: The Amora Formation, Mount Sedom, Israel: Geochimica et Cosmochimica Acta, v.71, no.15, p.A1031-A1031.

Turner, G. M., et al., 2007, Early Miocene magnetostratigraphy and a new palaeomagnetic pole position from New Zealand: Earth Planets and Space, v.59, no.7, p.841-851.

Zhu, R. X., et al., 2007, Are Chinese loess deposits essentially continuous?: Geophysical Research Letters, v.34, no.17,

Mineral & Rock Magnetism

Aydin, A., et al., 2007, The magnetic susceptibility of granitic rocks as a proxy for geochemical composition: Example from the Saruhan granitoids, NE Turkey: Tectonophysics, v.441, no.1-4, p.85-95.

Bae, C. J., et al., 2007, Experimental studies of strong dipolar interparticle interaction in monodisperse Fe3O4 nanoparticles: Applied Physics Letters, v.91, no.10,

Berquo, T. S., et al., 2007, Low temperature magnetism and Mossbauer spectroscopy study from natural goethite: Physics and Chemistry of Minerals, v.34, no.5, p.287-294.

Church, M. J., et al., 2007, Sourcing fire ash on archaeological sites in the Western and Northern Isles of Scotland, using mineral magnetism: Geoarchaeology-an International Journal, v.22, no.7, p.747-774.

Cullen, J., et al., 2007, Anisotropy of crystalline ferromagnets with defects: Journal of Applied Physics, v.101, no.12,

Franke, C., et al., 2007, Efficiency of heavy liquid separation to concentrate magnetic particles: Geophysical Journal International, v.170, no.3, p.1053-1066.

Fuji, T., et al., 2007, Large magnetic polarization of Ti4+ ions in FeTiO3: Journal of Magnetism and Magnetic Materials, v.310, no.2, p.E555-E557.

Modeling and Theory

Mata, G. J., et al., 2007, A quantum exchange bias model: Physica B-Condensed Matter, v.398, no.2, p.262-266.

Mazo-Zuluaga, J., et al., 2007, Surface anisotropy of a Fe3O4 nanoparticle: A simulation approach: Physica B-Condensed Matter, v.398, no.2, p.187-190.

NRM Carriers and Origins

Babinszki, E., et al., 2007, Widespread occurrence of greigite in the sediments of Lake Pannon: Implications for environment and magnetostratigraphy: Palaeogeography Palaeoclimatology Palaeoecology, v.252, no.3-4, p.626-636.

Maloof, A. C., et al., 2007, Sedimentary iron cycling and the origin and preservation of magnetization in platform carbonate muds, Andros Island, Bahamas: Earth and Planetary Science Letters, v.259, no.3-4, p.581-598.

Ron, H., et al., 2007, Greigite detected as dominating remanence carrier in late pleistocene sediments, lisan formation, from Lake Kinneret (Sea of Galilee), Israel: Geophysical Journal International, v.170, no.1, p.117-131.

Paleomagnetism and Tectonics

Abrajevitch, A., et al., 2007, Paleomagnetic constraints on the paleogeography and oroclinal bending of the Devonian volcanic arc in Kazakhstan: Tectonophysics, v.441, no.1-4, p.67-84.

Buchan, K. L., et al., 2007, Paleomagnetism, U-Pb geochronology, and geochemistry of Lac Esprit and other dyke swarms, James Bay area, Quebec, and implications for Paleoproterozoic deformation of the Superior Province: Canadian Journal of Earth Sciences, v.44, no.5, p.643-664.

Cifelli, F., et al., 2007, Tectonic evolution of arcuate mountain belts on top of a retreating subduction slab: The example of the Calabrian Arc: Journal of Geophysical Research-Solid Earth, v.112, no.B9,

Elming, S. A., et al., 2007, Palaeomagnetism and Ar-40/Ar-39 age determinations of the Ediacaran traps from the southwestern margin of the East European Craton, Ukraine: relevance to the Rodinia break-up: Journal of the Geological Society, v.164, p.969-982.

Garces, M. and Gee, J. S., 2007, Paleomagnetic evidence of large footwall rotations associated with low-angle faults at the Mid-Atlantic Ridge: Geology, v.35, no.3, p.279-282.

Gattacceca, J., et al., 2007, Miocene rotation of Sardinia: New paleomagnetic and geochronological constraints and geodynamic implications: Earth and Planetary Science Letters, v.258, no.3-4, p.359-377.

Hoshi, H. and Teranishi, Y., 2007, Paleomagnetism of the Ishikoshi Andesite: a Middle Miocene paleomagnetic pole for northeastern Japan and tectonic implications: Earth Planets and Space, v.59, no.7, p.871-878.

Itoh, Y., et al., 2007, Quaternary tectonic rotation in central Japan: Paleomagnetism of the Eboshidake volcanic rocks: Island Arc, v.16, no.3, p.457-464.

Moreau, M. G., et al., 2007, A new global Paleocene-Eocene apparent polar wandering path loop by "stacking" magneto stratigraphies: Correlations with high latitude climatic data: Earth and Planetary Science Letters, v.260, no.1-2, p.152-165.

Oliva-Urcia, B. and Pueyo, E. L., 2007, Rotational basement kinematics deduced from remagnetized cover rocks (Internal Sierras, southwestern Pyrenees): Tectonics, v.26, no.4,

Tarduno, J. A., 2007, On the motion of Hawaii and other mantle plumes: Chemical Geology, v.241, no.3-4, p.234-247.

ten Brink, U. S., et al., 2007, Magnetic character of a large continental transform: An aeromagnetic survey of the Dead Sea Fault: Geochemistry Geophysics Geosystems, v.8,

Thompson, M. D., et al., 2007, Late neoproterozoic paleogeography of the southeastern new England Avalon zone: Insights from U-Pb geochronology and paleomagnetism: Geological Society of America Bulletin, v.119, no.5-6, p.681-696.

Synthesis and Properties of Magnetic Materials

Edelman, I. S., et al., 2006, Magnetic nanoparticles in oxide glasses: Physics of Metals and Metallography, v.102, p.S2-S7.

Yanes, R., et al., 2007, Effective anisotropies and energy barriers of magnetic nanoparticles with Neel surface anisotropy: Physical Review B, v.76, no.6,

Ye, Q. L., et al., 2007, Effects of the unique shape of submicron magnetite hollow spheres on magnetic properties and domain states: Physical Review B, v.75, no.22,

Zhang, D. E., et al., 2007, Fabrication and characterization of Fe3O4 octahedrons via an EDTA-assisted route: Crystal Growth & Design, v.7, no.10, p.2117-2119.

***fitting*, continued from page 1**

evident why this should be the case. The best-determined quantity for our data set is its center of mass, ($\langle H \rangle$,$\langle M \rangle$). Unbiased random errors in the data have minimal effects on these mean values, but they have more "leverage" at higher or lower fields, causing the best-fit line to pivot around that point, and consequently a lower slope forces a higher intercept and vice versa[6].

Such correlated uncertainties arise from necessarily imperfect experimental design, which yields data sets that cannot perfectly discriminate between (or among) the variables of interest. In the ideal scenario for experimental parameter determination, the model basis functions are *orthogonal*, meaning in effect that the functions (and their corresponding parameter uncertainties) are uncorrelated.

Non-orthogonality of basis functions complicates matters especially when more than two parameters are to be determined, as we shall see. The worst case occurs when one or more basis functions can be expressed as linear combinations of the others; then the corresponding parameters can be constrained but not uniquely determined. For example, suppose we try to fit the same data using the function $M = \chi_P H + \chi_D H + M_S$, where χ_P and χ_D are respectively the paramagnetic and diamagnetic susceptibilities. Obviously these have exactly the same dependence on H, and whereas we may reasonably expect to obtain a best-fit value for the sum ($\chi_P + \chi_D$), we cannot hope to solve for them separately without additional (e.g., temperature-dependent) data.

Generalized Linear Least Squares

BRUTE-FORCE NUMERICAL INVERSION by systematic searching through a multidimensional parameter space, as above, is inefficient and rarely used. Smart multidimensional optimization algorithms such as the conjugate gradient method or simulated annealing quickly converge to optimal solutions, and in a great many cases the least-squares best-fit solution can be obtained in one fell swoop[7] by direct matrix-inversion methods including singular-value decomposition (see e.g. Press et al.[8] for details).

The classic way of introducing least-squares line fitting is to take partial derivatives of χ^2 with respect to the model parameters m and b (or χ_{HF} and M_S), set the derivatives equal to zero, and solve the resulting two equations for the two unknowns, whose values thus minimize χ^2. This approach quickly becomes difficult for complicated multiparameter functions; in general matrix methods are *much* easier to deal with, and yield identical results.

We can express the relationship between the dependent variables (the Nx1 data matrix $\boldsymbol{D}=(M_1, M_2, \ldots M_N)^T$, where T denotes transpose) and the linear model (the 2x1 parameter matrix $\boldsymbol{P}=(\chi_{HF}, M_S)^T$), through the Nx2 "design matrix" $\boldsymbol{A}$ (whose columns contain the model basis functions), as $\boldsymbol{D}=\boldsymbol{AP}$. The first column of $\boldsymbol{A}$ (the field-proportional basis function) is $(H_1, H_2, \ldots H_N)^T$, and the second column (the constant basis function) is filled with ones. For given parameters $\boldsymbol{P}$, we can calculate a model data set $\boldsymbol{D}$ by straightforward matrix multiplication. Inversely, for a measured data set $\boldsymbol{D}$ we can calculate the best-fit parameters as $\boldsymbol{P}=(\boldsymbol{AA}^T)^{-1}\boldsymbol{A}^T\boldsymbol{D}$. When the matrix $\boldsymbol{A}$ is first subjected to singular value decomposition (SVD), we obtain not only the best-fit parameter values, but also their individual and joint probability distributions.

Nonlinearity

IT IS OFTEN DIFFICULT to determine whether or not a linear model is fully valid, i.e., whether a data set comes entirely from the saturated zone of Fig 1 or whether it includes some of the more complicated approach-to-saturation regime. In this intermediate field range each magnetic particle is magnetized to saturation (i.e., only one domain remains) but the individual particle magnetizations are not perfectly aligned with the applied field.

Approach to saturation can be described mathematically by adding a nonlinear term to the linear model: $M = \chi_{HF}H + M_S + \alpha H^\beta$, where α and β are both negative[9]. β is related to the mechanisms governing the approach to saturation, and therefore it is of interest to quantify β experimentally. For moment rotation against magnetocrystalline or shape anisotropy in defect-free crystals, β~-2, and $|\beta|$ decreases with increasing defect density. For superparamagnetic material, the Langevin function approaches saturation with β~-1. Note that direct linear least-squares inversion methods cannot be used here, because M is a nonlinear function of β. In his excellent 2006 paper[9] Fabian outlines a method for determining α and β, to which we will return in a moment. First, however, let's look at two simple alternative approaches.

We can define a nonlinear magnetization model

$$M = \sum_{i=-2}^{1} a_i H^i = a_1 H + a_0 + a_{-1} H^{-1} + a_{-2} H^{-2}$$

which is amenable to direct least-squares treatment because, although it is nonlinear with respect to H, it is linear with respect to the model coefficients a_i. It is trivial to adapt the matrix approach described above to accommodate the two additional basis functions and coefficients. Figure 3 shows a close-up of the high-field data from Fig 1 and compares best-fit linear (dashed black line) and nonlinear (solid gray curve) models. Note that the differences between the best-fit curves are miniscule, and are most significant at the ends of the field range used for fitting.

For the linear model, the fit is excellent (R^2=0.9874) and the formal uncertainty is very small: both slope and intercept have standard errors less than 2% of the best-fit values. For the nonlinear model, the fit is slightly better (R^2=0.9934), but analysis of variance (ANOVA) tells us that the improvement is not statistically significant, meaning that we cannot confidently rule out the hypothesis that the true values of a_{-1} and a_{-2} are both zero. Moreover the best-fit value of a_{-1} is positive, which is not physically plausible. What is most disturbing, however, is that the best-fit values for the linear and constant terms are quite significantly different from those calculated for the linear model: M_S is about 10% higher and χ_{HF} about 98% lower (!) when nonlinear terms are included. These differences are many times larger than the standard errors for the linear regression.

Only two of the four parameters are well determined (a_0 and a_{-2}); for the others the standard errors are comparable to the best-fit values. The parameter variance-covariance matrix shows that the uncertainty in χ_{HF} is strongly (and negatively) correlated with those in both M_S and a_{-1}, all of which are more weakly correlated with the uncertainty in a_{-2}. Though not identical, the basis functions are clearly very far from orthogonal: the function $-H^{-1}$ can be fit very well (R^2=0.991) by a line over this field interval[10], and the same is only slightly less true for $-H^{-2}$ (R^2=0.980). Because of the similarity of these functions, they have a certain "interchangeability": a change in the value of a_{-1}, for example, can be compensated by changes in χ_{HF} and M_S to obtain a fit that is not significantly degraded (in almost the same way that χ_D and χ_P can be traded off against each other). As a result the confidence intervals are broadened enormously.

Let's return now to the doubly-nonlinear model $M = \chi_{HF}H + M_S + \alpha H^\beta$, in which M is linear with respect to neither field nor model parameters, and revisit our

cont'd. on p. 14…

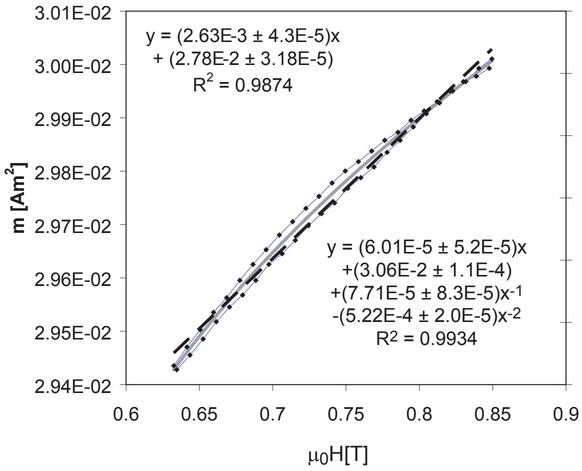


Fig 3. Is it perfectly linear? The best linear fit (dashed black line) differs only slightly from the best approach-to-saturation fit (solid gray curve) to the data (points and light curve). Best-fit parameter values χ_{HF} and M_S can change enormously when nonlinear terms are included.

primitive technique of systematically marching through the parameter space, with a slight refinement: we will choose a value for β, obtain the values for the remaining parameters (χ_{HF},M_S,α) by direct least squares inversion, calculate the misfit, and then proceed to the next value of β.

Figure 4 shows the results of such analysis for the same data set. The optimum value of β is approximately -2.0, and the misfit χ^2 grows parabolically as β deviates from the optimum value. Such quadratic dependence is typical in least-squares fitting, and is the basis of some of the more sophisticated numerical search algorithms (Press et al[8]). Because of the parabolic shape, the minimum is well determined but not sharp ($d\chi^2/d\beta \sim 0$ near β_{best}), and small differences in β result in only very minor degradation of the fit. As in the linear fitting, there are correlated uncertainties among the parameters, so that changes in β can be effectively compensated by changes in χ_{HF}, M_S, and/or α. In Fig 4, the changes in χ_{HF} are especially dramatic. Between β=-2.5 and β=-1.5, χ^2 changes by less than 2%, and the best-fit M_S stays within ±3%, but χ_{HF} ranges around its global best-fit value by more than ±3000%!

It is important to note that in the analysis above, we have used only data from the range between 70% and 95% of the maximum applied field, as is typically done for linear fitting. For optimal fitting of approach to saturation, it is far better to use a broader range extending to lower fields, where the distinction between linear and nonlinear basis functions becomes more pronounced. Reanalyzing the same loop using data down to 40% of H_{max} reduces the covariance of parameter probabilities, and yields tighter error bars. The best-fit β (~-2.2) is defined by a sharper minimum in χ^2 , which increases by almost 10% for small changes Δβ=±0.1, while M_S stays within ±0.5%, and the best-fit χ_{HF} range is limited to ±10%.

Fabian's approach[9] involves linearizing the problem and reducing the number of parameters (at least initially) by twice differentiating with respect to field (thereby eliminating the proportional and constant terms) and then taking logarithms:

$\log(|M''|)=\log|\alpha\beta(\beta-1)| + (\beta-2)\log(H)$.

A least-squares linear fit of $\log(|M''|)$ as a function of $\log(H)$ yields a slope and intercept from which α and β are easily determined, and their margins of error may be quantified. There is an interesting sort of "conservation of uncertainty" that comes into play here: each differentiation amplifies the noise in the measured data, so that the error bars become very large unless some careful smoothing is done first (and that is an art in itself).

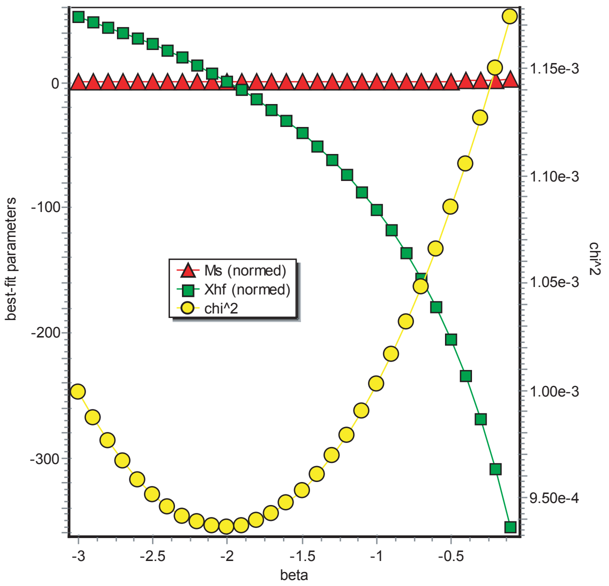


Fig 4. For all plausible values of β, pretty good fits can be obtained for the data of Fig 3 by adjusting the other parameters. Best β is -2, shown by minimum χ^2. Best-fit values of χ_{HF} and M_S are shown for each β, normalized to their value at β = -2.

The more you stir it... the more it will stink.[11]

ALL OF THE PRECEDING ANALYSIS assumes that measurement errors have a normal zero-mean probability distribution in each applied field. We can imagine and even quantify variance that changes as a function of applied field[12]. A more nefarious problem occurs when systematic errors change the distribution mean and its dependence on field. One example of this is the small but systematic changes that occur in conventional VSMs as the pole pieces approach saturation.

The distribution and intensity of magnetic flux surrounding a specimen together control the voltage induced in the VSM sensing coils. The flux distribution differs from that of an isolated magnetic point dipole for several reasons. The three-dimensional size and shape of the specimen is one that we have discussed previously[13]. Another is the interaction of the specimen flux with the high-permeability iron pole pieces of the electromagnet.

We can visualize this simply as a localized additional increment of magnetization in the pole pieces due to the field of the specimen. The effect is equivalent to having additional specimens vibrating inside the pole pieces. These virtual specimens are called magnetic images, by analogy with electrostatic images[14, 15]. The magnetic image effect improves the sensitivity of electromagnet-based VSMs, and is fully accounted for in instrument calibration, provided the pole piece permeability remains constant.

The field in the air gap of the electromagnet of course derives from the magnetization of the poles as well as the current in the coils. The practical upper limit on applied fields is due to the saturation of the pole pieces which, for typical configurations, corresponds to applied air-gap fields between about 1.5 T and 2.2 T. In this interval, as the poles approach saturation their permeability drops and the magnetic images of a specimen begin to "fade". This produces a downward curvature of the hysteresis loop (Fig 5) that can significantly affect the high-field magnetization fitting.

Summary and Recommendations

1. Quantifying uncertainty in experimentally-determined model parameters is just as important as determining the parameter values, but is complicated by the fact that we may not be aware of or able to account for all sources of error[16].

2. The more strongly correlated our basis functions, the larger the joint uncertainty in the corresponding coefficients. This is somewhat analogous to the paleomagnetic problem of obliquely intersecting great circles, or of triangulating from a narrow baseline to a distant point of interest: best-fit values become extremely sensitive to small errors in the data.

3. For most accurate determination of χ_{HP}, and M_S, it is (counterintuitively) not always best to use the highest available field range. In electromagnet-based VSMs, pole-piece saturation complicates matters. More generally, subtly and paradoxically, the fitting of nonlinear magnetization functions becomes ill conditioned when calculations are limited to narrow high-field ranges, with corresponding large increases in parameter uncertainties. In many cases χ_{HP}, and M_S, are determined more accurately by nonlinear fitting over wider ranges of intermediate fields. Confirmation using an instrument with a superconducting solenoidal magnet is helpful.

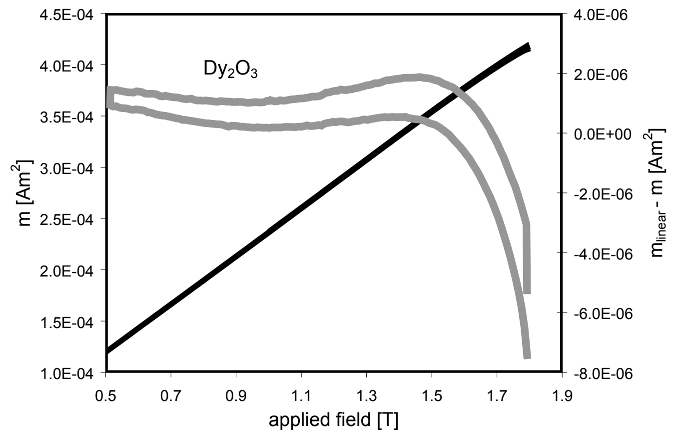


Fig 5. Effects of electromagnet pole-piece saturation are evident in these measurements on pure paramagnetic dysprosium oxide, where the magnetization (black) departs from perfect linearity in fields exceeding ~1.4 T. Gray curve shows deviations from best-fit line.

4. Least squares estimation for linear models is notoriously susceptible to skewing by outliers. This sensitivity is greatly amplified by the addition of nonlinear terms, and therefore more robust regression approaches (e.g., involving minimization of the "L_1 norm", the sum of absolute-value deviations) are worth a closer look.

References and Notes

1. "...as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns -- the ones we don't know we don't know." D. Rumsfeld, Feb. 12, 2002, Department of Defense news briefing.
2. e.g., 70% to 95% of the maximum applied field.
3. the origin of the (*m*, *b*) notation for slope and intercept is viewed by math historians as an interesting minor mystery, e.g., http://mathworld.wolfram.com/Slope.html
4. We assume that the control variable (field) is known exactly and that errors occur only in the *M* measurements, and thus we choose to minimize the *M* deviations alone, most commonly in the least-squares sense.
5. Gauss, C. F. "*Theoria combinationis obsevationum erroribus minimis obnoxiae*." Werke, Vol. 4. Göttingen, Germany: p. 1, 1823.
6. For more details see e.g. Borradaile, G.J., *Statistics of Earth Science Data: Their Distribution in Time, Space, and Orientation*, 351 pp., Springer Verlag, 2007.
7. This expression first appeared in *Macbeth*, when Macduff hears that his family has been murdered:
   "All my pretty ones?
   Did you say all? O hell-kite! All?
   What, all my pretty chickens and their dam
   At one fell swoop?"
8. Press, W.H., B.P. Flannery, S. Teukolsky, and W.T. Vetterling, *Numerical Recipes: The Art of Scientific Computing*, 814 pp., Cambridge University Press, Cambridge, 1986.
9. Fabian, K., Approach to saturation analysis of hysteresis measurements in rock magnetism and evidence for stress dominated magnetic anisotropy in young mid-ocean ridge basalt, *Physics of the Earth and Planetary Interiors, 154*, 299–307, 2006.
10. There is an additional parameter implicit here, a field scaling constant H_0, so that the power-law function uses a dimensionless (normalized) field, H/H_0. We follow Fabian's scaling with $\mu_0 H_0 = 1$ Tesla.
11. *Don Quixote* vol I Book 3 Ch 6.
12. e.g., Carter-Stiglitz, B.S., B.M. Moskowitz, and M.J. Jackson, Unmixing magnetic assemblages, and the magnetic behavior of bimodal mixtures, *Journal of Geophysical Research B: Solid Earth, 106* (B11), 26,397-411, 2001.
13. *IRM Quarterly* v. 11 n. 4, 2001-2002.
14. Hoon, S.R., and S.N.M. Willcock, The direct observation of magnetic images in electromagnet vibrating sample magnetometers, *Journal of Physics E: Scientific Instruments*, 21, 480-487, 1988.
15. I thank Harry Reichard of Princeton Measurements Corp for bringing this effect to my attention.
16. Scientific uncertainty looms especially large where the spheres of science, public policy and politics overlap; see e.g., Pollack, H.N., Scientific uncertainty and public policy: Moving on without all the answers, *Geological Society of America Today*, 17, 28-29, 2007.

University of Minnesota
291 Shepherd Laboratories
100 Union Street S. E.
Minneapolis, MN 55455-0128
phone: (612) 624-5274
fax: (612) 625-7502
e-mail: irm@umn.edu
www.irm.umn.edu

Nonprofit Org.
U.S Postage
PAID
Mpls., MN
Permit No. 155

The IRM Quarterly

The *Institute for Rock Magnetism* is dedicated to providing state-of-the-art facilities and technical expertise free of charge to any interested researcher who applies and is accepted as a Visiting Fellow. Short proposals are accepted semi-annually in spring and fall for work to be done in a 10-day period during the following half year. Shorter, less formal visits are arranged on an individual basis through the Facilities Manager.

The *IRM* staff consists of **Subir Banerjee**, Professor/Director; **Bruce Moskowitz**, Professor/Associate Director; **Joshua Feinberg**, Assistant Professor/Associate Director; **Jim Marvin**, Emeritus Scientist; **Mike Jackson**, **Peat Sølheid**, and **Thelma Berquo**, Staff Scientists.

Funding for the *IRM* is provided by the **National Science Foundation**, the **W. M. Keck Foundation**, and the **University of Minnesota**.

The *IRM Quarterly* is published four times a year by the staff of the *IRM*. If you or someone you know would like to be on our mailing list, if you have something you would like to contribute (*e.g.*, titles plus abstracts of papers in press), or if you have any suggestions to improve the newsletter, please notify the editor:

Mike Jackson
Institute for Rock Magnetism
University of Minnesota
291 Shepherd Laboratories
100 Union Street S. E.
Minneapolis, MN 55455-0128
phone: (612) 624-5274
fax: (612) 625-7502
e-mail: irm@umn.edu
www.irm.umn.edu

UNIVERSITY OF MINNESOTA

2008 International Conference on Rock Magnetism

June 2-7, 2008, Cargèse Corsica
Institut d'Études Scientifiques de Cargèse
(see inside for details)

www.cargese.net